Cities 95 (2019) 102358

Contents lists available at ScienceDirect

Cities

journal homepage: www.elsevier.com/locate/cities

A complexity approach to defining urban energy systems

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ARTICLE INFO

Keywords:
Urban energy systems
Complex systems
Agents
Networks
Context

ABSTRACT

Urban energy systems have been commonly considered to be socio-technical systems within the boundaries of an urban area. However, recent literature challenges this notion in that it urges researchers to look at the wider interactions and influences of urban energy systems wherein the socio-technical sphere is expanded to political, environmental and economic realms as well. In addition to the inter-sectoral linkages, the diverse agents and multilevel governance trends of energy sustainability in the dynamic environment of cities make the urban energy landscape a complex one. There is a strong case then for establishing a new conceptualisation of urban energy systems that builds upon these contemporary understandings of such systems. We argue that the complex systems approach can be suitable for this. In this paper, we propose a pilot framework for understanding urban energy systems using complex systems theory as an integrating plane. We review the multiple streams of urban energy literature to identify the contemporary discussions and construct this framework that can serve as a common ontological understanding for the different scholarships studying urban energy systems. We conclude the paper by highlighting the ways in which the framework can serve some of the relevant communities.

1. Introduction

Cities account for two-thirds of global primary energy demand that makes understanding of urban energy systems central to sustainable transitions (Grubler et al., 2012; Rambelli, Donat, Ahamer, & Radunsky, 2017). The Paris Climate Agreement added further traction to the growing international clout of cities as potent actors in both climate change mitigation and adaptation interventions (Rambelli et al., 2017). Within academia, the link between cities and climate change has been undergoing significant transformation over recent years; from being viewed as challenges for energy demand management and efficiency to being hailed as 'key sites' or 'opportunities' for energy interventions and innovations (Broto & Bulkeley, 2013; Grubler et al., 2012). Transition to a centralised grid system of energy supply led to cities being viewed as 'passive centres of demand', that took away the "urbanness" of these energy systems (Rutter & Keirstead, 2012). However, new technological possibilities and governance perspectives have challenged this simplified view and thus necessitate an alternate or new conceptualisation of UESs (Urban Energy Systems) that can serve as a common cross-disciplinary framework of understanding. This paper attempts to take the first step in this direction.

It is the socio-technical and urban studies that firmly grounded the techno-economic pursuits of energy systems into the social structure of cities (Webb, Hawkey, & Tingey, 2016). However, contemporary literature from different scholarships has added much to this understanding of UESs. We try to summarise a few major aspects here. Firstly, the relocalisation of responses to urban energy issues beyond the ambit of energy demand quantification and simulation indicate the decentralising trends of both policy making and interventions (Bulkeley, 2010; Rutherford & Coutard, 2014).[2] This trend embodies accounting for the multiple heterogeneous actors and hierarchical centres of decision making and formulation of strategies and responses that are localised, contextual and embedded in socio-cultural practices (Broto, 2015; Bulkeley, Broto, Hodson, & Marvin, 2011; Moss, 2014; Shove, 2017). Secondly, the literature increasingly acknowledges the need to take a comprehensive or composite outlook when designing, managing and governing UESs. Scholarships involving quantitative analysis like urban energy modelling and urban metabolism have invoked the need

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[2] Also see Grubler et al. Page 1325 on the need to look at energy system from an urban lens.

https://doi.org/10.1016/j.cities.2019.05.027
Received 13 November 2018; Received in revised form 24 March 2019; Accepted 24 May 2019
Available online 27 June 2019

for an integrated understanding of urban energy referring to the interlinkages of different sectors and the related material flows within the urban area that have deep implication for the energy system (Bai, 2016; Grubler et al., 2012; Keirstead, Jennings, & Sivakumar, 2012). The social sciences scholarship on urban energy, on the other hand, calls for understanding the interdependencies of the non-material facets of the urban i.e. the historical, cultural, political and the societal at large with the materialities of UESs (Bulkeley et al., 2011; Monstadt, 2009; Moss, 2014). Study of the interconnected and interdependent nature of cities' energy systems is a major theme in both these literature streams. The third major understanding that has gained consensus across the disciplines is the fact that UESs are deeply embedded within the national, and in some cases international infrastructures, processes and institutions. While large infrastructure systems and the urban metabolism literature look at the interdependency of cities and external environments (Bai, 2016; Monstadt, 2009; Rutherford & Coutard, 2014), governance and political enquiries look at the influence of decision making, policies and politics of institutions at higher levels (Bulkeley et al., 2011; Jaglin, 2014; Rutherford & Coutard, 2014).

These contemporary multidisciplinary insights, developments and understandings of the urban energy sector indicate the need for a new ontology and approach and possibly a shared comprehensive framework for UESs. In this paper, we argue that this could be realised through a complex systems approach (Bale, Varga, & Foxon, 2015; Rutter & Keirstead, 2012).

In line with this, we propose such a framework that embraces, traces and maps the complexity of UES that constitutes the scope, potential, constraints, linkages and interactions of the system through an understanding of the agents and other elements, their networks as well as the interdependent subsystems. In much the same way that Elinor Ostrom proposed that "A common, classificatory framework is needed to facilitate multidisciplinary efforts toward a better understanding of complex SESs (Social-Ecological Systems)" we here propose that those involved in research domain of UESs across different disciplines need a common framework of understanding through the complex systems approach; as "without a framework to organize relevant variables identified in theories and empirical research, isolated knowledge acquired from studies …is not likely to accumulate" (Ostrom, 2009).

2. Urban energy complex systems – An integrating approach

As an integrating element, complexity theory provides not a methodology per se, but rather "a conceptual framework, a way of thinking, and a way of seeing the world" (Mitleton-Kelly, 2003). The Complexity Academy characterises a complex system as one with heterogeneous and diverse elements that enjoy a certain degree of interconnection and agency that lets them adapt to changes over time (Crawford, 2016). Thus, it essentially shuns the reductionist approach of the prevailing centralised lenses of understanding urban or energy systems (Salat & Bourdic, 2012). Complexity science also offers a set of theories and tools for exploring complex adaptive systems - systems noted for often quantifiable and non-quantifiable properties that include self-organisation, hierarchy, emergence, evolution, path dependence, adaptive behaviour and non-linearity (Crawford, 2016; Mitchell, 2009; Simon, 1962).

2.1. Cities as complex systems

Cities have been understood as complex adaptive systems in the academic literature long before energy systems (Allen, 1984; Forrester, 1969). Batty and Marshall (2012) claim that complexity or complex systems thinking was repeatedly revived in the urban planning discipline because of the felt inadequacy of the centralised top down planning approach (Batty & Marshall, 2012). As aptly put by Salat and Bourdic (2012), "the aim of a complex approach to the city is to bring together different forms of knowledge whose connections have been broken by disjunctive thinking". Therefore, a complex systems approach has helped in bringing an integrative plane and formalisation to the different concepts from the multiple sub disciplines of urban studies. Scholars of this field have visualised cities as both multiscalar, hierarchical, interconnected and multidimensional. Batty and Marshall (2012) aptly express cities to be open systems or "ecosystems" a view that has progressed from the earlier accepted view of "organisms" (Batty & Marshall, 2012); this transition has also been subscribed by the urban metabolism scholarship (Bai, 2016). Demonstrating this, Desouza and Flanery (2013) summarise that complex systems conceptualisation of cities brings together the concepts of subsystems, physical, social and other components, networks, feedbacks and interactions (Desouza & Flanery, 2013). The complexity of cities arises, therefore, due to the overlapping, interconnected and hierarchical nature of these elements or subsystems of urban areas leading to urban level dynamics (flux), emergence, ability to self-organise and adapt and co-evolve (Crawford, 2016; Desouza & Flanery, 2013).

This contemporary lens, in the discipline of urban studies, has helped bring to light the following paradigmatic aspects to city planning: 1) the need for a bottom up approach to planning cities that is rooted in the heterogeneous agents and local context (historical evolution, functional make-up, spatial patterns); 2) the understanding of cities as constituted by multiple subsystems (including the human subsystem); 3) a departure from the broader objective of attaining equilibrium or optimality in city planning and embracing the unpredictability in planning practices (Batty, 2009; Batty & Marshall, 2012; Desouza & Flanery, 2013; Johnson, 2012).

2.2. Energy sustainability and complex systems

Complex systems understanding of energy systems has been increasingly relevant with the developments of the energy sector – whether technologies (decentralised energy systems (DESs) and consumption interventions); neoliberal governance principles (market dynamics and private actors); call for behavioural, participatory, community-oriented and polycentric collaborative approaches. Complex systems approach in energy was conventionally limited to understanding the thermodynamics of energy systems. However, growing number of academic studies have contended that the energy systems exhibit complex systems attributes, primarily, due to the interactions of a heterogeneous set of elements ('agents and objects'), capable of exchanging energy and material and non-material things within a given 'environment' with little 'autonomous control' or regulation (see (Bale et al., 2015; Houwing, Heijnen, & Bouwmans, 2007; Mercure, Pollitt, Bassi, Viñuales, & Edwards, 2016). LaBlanca (2017) further adds that the complexity of energy systems increases with an increase in the number of nodes or elements that can act as subsystems themselves. This makes these systems inherently hierarchical where each element within the subsystem can act as a subsystem itself. Several studies have further empirically demonstrated within energy systems, individual properties closely associated with complex systems like co-evolution, self-organisation, network dynamics as a result of these heterogeneous set of interactions (Bale, Foxon, Hannon, & Gale, 2012). The conceptualisation of energy systems as complex systems, however, has been primarily the domain of the energy modelling community till now and has driven the paradigm shift of models assuming a 'prescriptive or descriptive' role rather than a normative role (Mercure et al., 2016). Unpredictability and non-equilibrium are the contemporary understandings of energy systems arising out this approach (Bale et al., 2015; Mercure et al., 2016). Agent based modelling, specifically, in relation to distributed energy technologies, have further showcased the emerging complexities in the interactions of the different agents when they can also potentially generate and exchange energy locally (Fichera, Pluchino, & Volpe, 2018; Fichera, Volpe, & Frasca, 2016).

The discussions within these streams of scholarship indicate a potential ontological compatibility between the understandings of the urban and energy systems. The framework of understanding offered by this paper lies at the intersection of these two systems thus building a comprehensive view of UESs.

3. Methodology

For building the framework, we broadly use the methodology proposed by Jabareen (2009) - a methodology proposed for "phenomena that are linked to multidisciplinary bodies of knowledge" (Jabareen, 2009). In line with this, we follow the definition and features of conceptual framework wherein Jabreen describes a conceptual framework as "a plane," of interlinked concepts that together provide a comprehensive understanding of a phenomenon or phenomena.

A phased methodology involving a mix of expert interviews and literature review was carried out to arrive at the framework presented in section 4. As a first step, up to six urban and energy scholars were interviewed to understand the broad contours of contemporary discussions and debates of energy in urban areas. Secondly, in addition to the review of general complex systems theories a multi-disciplinary literature review was conducted for contemporary understandings of UESs. The literature can be categorised as below:

- Energy studies: We focussed, firstly, on socio-technical discussions within energy studies that span across smaller sub-groups of disciplines like energy governance, sustainability transitions, energy modelling.
- Urban studies - Within the vast literature that occupies urban studies, we limited our enquiry to firstly, complex systems explorations by urban scholarship that spans across fundamental conceptualisation of cities, urban planning, modelling and governance studies and secondly, broader sustainability studies within an urban domain with a focus on socio-ecological and socio-spatial understandings of cities.

The resulting complex systems-based framework brings together the multitude aspects or concepts related to urban energy most commonly discussed in these different disciplines to propose a new understanding or conceptualisation of UESs. It establishes a new visualisation of UESs and provides with a comprehensive structure through a complexity lens.

Lastly, an iterative process was followed to formalise and validate the framework through formal discussions with academic experts and researchers in the urban sustainability sector (for detailed step wise methodology see (Jabareen, 2009)).

4. Conceptualising complex urban energy systems

4.1. Approach

While subscribing to the idea that a complex system description is dependent on the point of view of the researcher (Cilliers, 1998; Kljajiae, Škraba, & Bernik, 1999), our approach towards building this framework is to map the UES in its entirety, complete with its structure, layers and elements, along with their networks, interactions and interlinkages with other elements of a city. This largely follows the complex systems characteristics highlighted by Cilliers (1998).[3]

Keeping the above approach in mind, we characterise UES as:

- Multi-layered components and interactions - The UES is a highly interconnected set of heterogeneous urban material and non-material elements, including agents, integrated into a multi-layered structure by virtue of acquiring, producing, delivering and using energy and energy linked services.
- Hierarchical and interlinked - It is clearly hierarchical in that it is interdependent on the agent and by that virtue institutional organisations and interactions at different levels. Therefore, it is linked to upstream processes of extracting, producing and supplying the energy irrespective of its location (within or outside the administrative boundary of the city) that involve international markets, infrastructures, governments and other exogenous factors affecting energy processes to individual decision-making surrounding adoption, use energy technologies and services and even generation and exchange of decentralised power in the urban areas.
- Contextual and socially embedded – These elements are deeply embedded in the local context of the city that embodies the historical evolution, local economic activities, infrastructural form and ecological conditions, consumers and their behaviour, cultural considerations and larger societal configurations and institutions. Thus, they both shape and are shaped by the particular local context of a city.
- Part of a larger urban system **–** UESs are only one part of the other interconnected and interdependent systems that make up the city. The energy system within a city is invariably linked to the other natural/ecological and infrastructural and resource-based systems that altogether make up the city. These lateral adjacent systems within the boundaries of a city both influence and are influenced by the input or output variables for the energy system.

By taking a deep dive into urban arena within which the energy system is embedded, the framework explicitly recognises the different layers within the subsystem (categorising the different elements of the system in accordance to their structural interactions), its interplay with other multiple subsystems including the contextual factors within the boundaries of the urban region. What makes the system complex is the fact that the system and its elements neither exist in isolation nor are static, enjoy a certain degree of agential independence (Peter & Swilling, 2014) and hence capable of emergence, self-organisation and produce feedback loops.

4.2. Scope

As implicit in its definition, complex systems can present themselves as an unending set of interacting subsystems that each then comprises of agents/elements/actors, interacting through networks and exhibiting dynamic aspects or emergent properties and adaptive and learning processes. In fact, it is appropriate to conceptualise an urban area as a 'system of complex systems' (Ghauche, 2010). To be able to comprehend, govern or model, one would need to clearly define the boundary or scope of the system of the investigation while keeping an overview of the impacts of interacting systems (Cilliers, 2001). It also helps in defining a model, collecting data and embracing the system (Bale et al., 2015). Defining the boundary for a complex system, however, can be tricky due to the open nature of these systems where interaction amongst the components or other related subsystems is equally, if not more, important than the components themselves (Cilliers, 2001). Ryan (2007) helps in describing the typical manner of defining the scope of a system wherein scope is set as per the intensity of interactions and 'system boundary is chosen to separate the system from its environment where the interactions are weakest' (Ryan, 2007). Therefore, a gradience in the strength of interaction is a key feature of complex systems. In keeping with this principle, instead of defining the scope, we focus the framework on two parameters; 1) the urban area and, 2) within that, the energy subsystem. A note of caution may be sounded here as emphasised by several complexity science scholars that an overemphasis on boundary may lead to the undermining of broader environmental linkages (Cilliers, 2001). While boundaries cannot be done away with, they can be considered to play a facilitative role rather than an obstructive one.

[3] See definition of Complex systems by Cilliers, 1998 (Cilliers, 1998)

4.3. City subsystems

In early complex systems literature, all complex systems have been considered to decompose into a nested hierarchy of subsystems that in turn have their own subsystems (Simon, 1962). Therefore, while each subsystem is nothing different than the interaction of different components, each of these components however can be subsystems or be part of another subsystem and therefore exhibit the corresponding characteristics of those subsystems (Johnson, 2012). Identification and the number of subsystems often depend on the unit of investigation and resolution desired in the research. Johnson (2012) conceptualises cities as "systems of systems of systems" (Johnson, 2012); in that he identifies the hierarchical arrangement of subsystems. He contended that the broader conceptual subsystems can be categorised as 'physical'/'technological' and 'social' while the functional subsystems can be considered as the second-tier/'*meso* level' subsystems within a city that help run the city – sectors of water, transport, environment, economy, amongst others.[4]

Our entry point for this framework is the energy subsystem situated along with the many subsystems of the city with significant overlaps and interconnections with these other subsystems. This energy subsystem also interacts with systems external to the city system (See Section 4.1). For instance, energy systems in a city are critically connected with the national infrastructure as they are connected with the exogenous dynamics of the international markets, fuel prices, technology and finance availability; on the other hand, the energy subsystem directly interacts with or impacts the other same level economic subsystems like commercial, industries, agriculture, water and other infrastructure subsystems and the natural subsystem as a whole (air pollution, heat island, black carbon emissions). The acknowledgement of deep interactions, interdependencies and feedback amongst different subsystems is one of the major contributions of a complex systems framework.

4.4. Urban energy system: Constitutive elements

4.4.1. Context

The significance of local context in the energy system has been acknowledged recently in the Socio-Technical Studies (STS) literature wherein recent discussions in energy interventions have challenged the dominant paradigm of abstracting energy systems out of their context for further investigation, management or governance (Cajot, Peter, Bahu, Koch, & Maréchal, 2015; Cilliers, 2001; Ghauche, 2010; R. Webb et al., 2017). The significance of local context finds appropriate expression in urban complex system studies. Batty and Marshall (2012), pioneers of complexity approach in urban planning, argue that a city needs to be seen as evolving out of its geographical and historical predisposition through a "complex web of causes and effects, its inter-related parts interwoven through time" (Batty & Marshall, 2012). This is a key aspect that renders a city its complexity (Batty & Marshall, 2012). Thus, local context differentiates systems in urban areas from their larger whole. The way the city subsystems organise themselves in response to temporal events and changes is key to understanding urban areas. Local context manifests itself through the physical and social systems creating the conditionalities for energy implementation and processes but is also simultaneously shaped by not just the energy subsystem but also the rest of the subsystems interacting with the local context.

While the importance of context cannot be dismissed in a system embedded in societal systems, it is undeniably an abstract concept and cannot be quantified or modelled. In this paper and framework, we make a contribution by opening up the black box of context and highlighting the possible aspects influencing or constituting the context subsystem. We define context based on complex systems understanding as (Pfadenhauer et al., 2016):

> *"a set of characteristics and circumstances that consist of active and unique factors that surround the implementation. As such it is not a backdrop for implementation but interacts, influences, modifies and facilitates or constrains the intervention and its implementation. Context is usually considered in relation to an intervention or object, with which it actively interacts."*

This definition allows to frame context as a separate (sub)system/phenomenon that forms the dynamic environment(s) in which urban energy implementation processes are situated (May, Johnson, & Finch, 2016). In the case of energy, literature points to multiple factors that may constitute context - ranging from geographical restrictions or natural resources made available by *physical landscape*; *historical evolution* of an urban area that typically shapes the local activities, culture and perceptions; *economic diversity* that make up the commercial and resource flows that determine the dominant sectors, employment and growth rates and income distribution; *social heterogeneity* arising from these factors manifesting often in household types, education levels, access to resources and information amongst others; *spatial patterns* and urban form that arise from the land-use linked to this heterogeneity and lastly the *political narratives* that are built to run the energy system.

4.4.2. The energy subsystem

The energy system, being an action or a functional subsystem, can be broadly segregated as 1) agents or actors arising out of the social subsystem indicated above, 2) material elements to produce, consume and deliver energy and 3) interactions between these elements to deliver the function (Bale et al., 2015; Holtz, Brugnach, & Pahl-Wostl, 2008). Interactions between these multi-layered elements take place through both materials (energy, capital, etc.) and non-material flows like that of knowledge, perceptions, social practices, rules, etc. (Bale et al., 2015). These varied interactions lend the key characteristics to the system and also structure the entire system.

I) **Agents**: Agents form the social component of energy systems. They have been defined essentially as heterogeneous autonomous actors (or groups of actors) with decision making, interacting and influencing powers (Bale et al., 2015), (Macal, 2012). Agents interact and are coupled in the system, and importantly, are able to adapt, learn and respond to other agents or the conditions of the environment. Bale et al. (2015) further characterise agents to be interacting through networks under the influence of institutions, which gives rise to emergent properties and co-evolutionary dynamics. Every agent is defined by three interlinked aspects of 1) specific attributes (Holtz et al., 2008), 2) behaviour and decision making powers shaped by attributes and context that can evolve and change through time (Bale et al., 2015; Shove, 2017) and lastly 3) channels of communication and influence (networks) (Lablanca, 2017).

With the onset of discussions from behavioural sciences and contemporary governance perspectives within energy transition studies, there has been a deeper enquiry regarding the nature, types and roles of agents within urban energy (Macal, 2012). Literature has segregated the broader category of agents and actors within energy systems on the basis of 1) basic function within the system (consumers, producers, etc.) (Bale et al., 2015) and 2) nature (individuals, households, firms, corporations, etc.) (Ruzzenenti, 2017) or 3) advanced political or governance oriented roles (state, non-state, niche or regime actors) (see transitions literature (Fischer & Newig, 2016)). Taking a cue from the

[4] Literature has also considered hierarchy to be inherent to complex systems in two further ways:1) Hierarchies as levels of organisations (see Salat, 2012); 2) Hierarchy is also conferred to complex energy systems due to the different levels of decision making, especially in view of distributed energy generation systems in case of renewable energy systems (see LaBlanca, 2017).

wider literature, we propose a basic typology of agents basing on their foundational roles within a UES:

- *Users*– End users of energy services – and not just consumers - are typically further segregated based on their functional attributes like a household, municipal, commercial, industrial and in some cases even agricultural each exhibiting specific demand type and patterns (Grubler et al., 2012; Rounsevell, Robinson, & Murray-Rust, 2012). It is the formal understanding beyond this categorisation that has received little attention. Open boundaries, unequal economic development patterns, and other dynamic contextual aspects, lead to a widely diverse and heterogeneous set of users in a city adding to the complexity of urban system further. The literature points to high heterogeneity even within the single category of households especially in terms of the energy use behaviour patterns, adoption capabilities, building size due to varying socio-economic status (McKenna, Hofmann, Merkel, Fichtner, & Strachan, 2016). This is also relevant in case of urban areas in developing countries where the prevalence of low income households or informal settlements existing alongside gated communities with often 24-hour, 7 day power back-up is quite common (Grubler et al., 2012). To paint all this diversity under a single unit of users does not help in understanding urban energy users. This kind of heterogeneity can also be extended to the other user groups of industrial, commercial, municipal consumers depending on their different attributes like size, energy consumption, activities etc. The granularity of considering this heterogeneous nature of users (individual users, in case of agent-based modelling (ABM) for instance, or broad functional categories) will be a factor of the object of the investigation.[5] An increasingly acceptable level in the user centric complexity literature is an intermediate one i.e. known as *clusters or archetypes* (Bale et al., 2015; Rounsevell et al., 2012). Zhang, Siebers, and Aickelin (2012) were able to identify eight archetypes of the user group residential energy consumer in the entire UK (Zhang et al., 2012) while Kubota, Surahman, and Higashi (2014) were able to identify three clusters of household types in just two cities of Jakarta and Bandung under different criteria (Kubota et al., 2014). Attributes of each of these clusters or archetypes are heavily shaped and influenced by the agent environment or local context (see earlier section on context) of the individual cities and are collectively reflected in their final behaviour and decision-making pattern with the energy technologies. Therefore, each of these identified cluster types or archetypes then exhibit a unique behaviour in its interaction with the energy infrastructure in return for energy services.
- *Providers*– This second agent group in the system are primarily entities that are responsible for the provision and management of energy and related infrastructure and services including managing energy related infrastructure within the city limits (Adil & Ko, 2016; Mitchell, 2010). This will typically include organisations or businesses who have been traditionally responsible for managing the local grid like distribution utilities, billing and local electricity procurement entities like local electricity companies, heat or cooling supply network managers, transport network managers, builders, amongst others. At the core of the existence of this agent group are the investments for implementation of this infrastructure, and technologies through different business strategies and the revenue received from them through the user groups. Over the years, the framings of energy provision have also evolved from the notion of pure energy supply to the provision of an energy service that fulfils a specific function for the user. This has also led this agent group to evolve from assuming the role of just suppliers to providers of energy services and that resulted in efforts towards innovation in technology, services and business strategies (Energy service companies or ESCos for instance). With the incidence of liberalisation in the power sector in most countries and possibilities under decentralised renewable energy systems, the number and variety of players in this category have increased. Newer actors like local energy generators, suppliers of equipment, installers and maintenance for distributed energy systems, service providers, aggregators, and energy efficient appliance suppliers find their foothold in this space. Distributed energy systems are also ushering a new type of agent group that are blurring the distance between providers and users.[6] Agents who have traditionally been consumers of energy supplied by centralised utilities are increasingly shifting to the role of producers of energy for self-consumption as well as sale of excess of energy - a category popularly called prosumers (Adil & Ko, 2016; Fichera et al., 2018). This is facilitated by the increasingly decentralised modes of energy technologies. Fichera et al. (2018) also outline that this has resulted in exchange of excess energy amongst multiple user groups. This phenomenon significantly complexifies the urban energy landscape as the role of a single agent is now fluid and not passive; giving rise multi-directional interactions between these agents. Users are known to also contribute as providers of energy technology by serving as innovators or entrepreneurs and additionally influencing the overall ethos of the business community. On another hand, providers, as a category, also exhibits heavy dependence and feedback from the national infrastructural policies and regulations and national and international economic dynamics and other exogenous factors (cost of fuel, domestic content requirement policy, equipment prices, tax regime etc.).
- *Institutions:* Rounsevell et al. (2012) characterise institutions as organisations that "can also play the role of agents with the heterogeneous agent attributes, a unique goal-orientation, and rule-driven behaviours and interactions with other agents and their environment" (Rounsevell et al., 2012). Scholars in transitions and governance are also increasingly highlighting the significance of agents that are neither consumers nor suppliers of energy and also often act as intermediary organisations (Fischer & Newig, 2016; Hodson & Marvin, 2010). Clubbing such agents under the rubric of 'institutions', we conceptualise institutions as agents involved in locally shaping the individual agents and interactions as well as an overall system through regulations, incentives, communications, financial and knowledge support but not necessarily participating in the direct transaction process of an energy system. Therefore, this would include not only the local energy governing bodies but also the other support and intermediary organisations and citizen groups that have an influence on the other agents in the system.

II) Interactions – Interactions between the different elements of complex systems give the system under consideration its inherent structure (Cilliers, 2001). Key characteristics of complex system interactions amongst elements have been thought to be nonlinear, fairly short range and exhibiting feedback dynamics (Cilliers, 1998; Richardson, 2006). The non-linearity of interactions along with their causal and non-causal characteristics define the complexity of the system to a large extent. While interactions are used as a generic term for all interrelationships within a complex system, we differentiate between three types of interactions broadly:

- Agent-technology Interactions – A composite outcome of the 1) agent attributes 2) context, and 3) social and institutional networks of agents is the unique and diverse ways in which users interact with energy infrastructure and its artefacts. Each interaction could be further qualified as a representation of user behaviour, preferences,

[5] Also see Grubler et al., 2012 (page 1331, Fig. 18.6)

[6] LaBlanca (2017) characterises this large-scale transition from centralised generation of power to distributed and interconnected locations that can also potentially serve as centres of consumption as complexification of the energy sector.

adoption, investment, facilitation or payment for artefacts or services etc., which are different for each actor and sub actor groups. For instance, clusters of large corporate bodies and growing entrepreneurial start-ups within the user group of a commercial sector of a city would interact in very different ways with the energy infrastructure. Each of these unique interactions can emerge as city-wide energy consumption and pattern, demand for artefacts, innovation and adoption capabilities, and even payment capabilities. This understanding could potentially foster much more targeted and effective policy and governance instruments that cater to specific requirements of each user cluster.

- Networks – In addition to the interaction amongst different core elements, a prominent feature of the complex system is the incorporation of the concept of networks used by agents to interact between themselves (Bale, McCullen, Foxon, Rucklidge, & Gale, 2014). Network concepts also have gained attention in transition theory and innovation theory often used to study sustainable energy transitions (Edsand, 2016; Loorbach, 2010). Networks have been identified as physical and social networks typically to exchange information, learning, communication, etc. (Bale et al., 2014). However, the varied nature of agents also merits understanding networks within other agent groups i.e. beyond the realm of just social networks. Networks amongst agents can be thought to differ based on agent type:
  - o *Social Networks:* Social networks are primarily networks of communication and influence mostly amongst the social agents of the city (users). The degree of influence may vary 1) within clusters, 2) between clusters of the same User group and 3) amongst different user groups. Socio-technical energy system related literature widely acknowledges the role of social networks in influencing the adoption and diffusion of innovations (technologies and behaviours) in distributed energy systems (Adil & Ko, 2016; Puzzolo, Stanistreet, Pope, Bruce, & Rehfuess, 2013; Zhang et al., 2012). The concept can be further extended to other agent groups as well. Networks within industries or commercial user groups have been well established in the past. The industrial network in the Ruhr region (Initiativkreis Ruhr)[7] is one such example, where industries/firms have benefitted from the exchange of knowledge and practices on sustainable interventions. Further, inter user groups can also be expected to influence each other although the nature of influence will be vastly different. For instance, commercial sectors like hotels or other services would like to mould their technology practices towards the sensibilities of their customers.

    An emerging set of interaction is linked to increasing numbers of prosumers participating in the energy market through locally produced energy enabled through distributed energy systems. The complex set of interactions between consumers, prosumers (consumers producing energy) and the traditional energy suppliers materialises through both social network as well as the infrastructural layer[8] (Fichera et al., 2018, 2016). Multiple interactions of this nature are also likely to impact grid stability and peak demand of the city.
  - o *Provider networks* – Networks amongst public and private enterprises can be expected to be of more commercial nature. Partnerships, competition or even commercial arrangements or complimentary firms can improve the supply or provision of energy related technologies or boost innovation multi-fold.
  - o *Institutional networks* – While this topic under this terminology is much less discussed, channels of influence amongst different types of institutions finds some space in research. There is still much scope in the literature for further exploration of institutional networks that result in influencing UESs.

- *Feedback* - Feedbacks can be conceptualised as mostly direct or indirect influences (often causal) that agents and their interactions within the complex system can have on other components, agents or even linked subsystems (Allen, 2012). The feedback phenomenon can induce positive influences or even negative influences almost as an externality to the central interaction and is also bi-directional creating a continuous loop. The nature of feedback is often difficult to trace or define but cannot be ruled out from our understanding. Therefore, feedback usually does not involve direct transactions but mostly a cycle where the output of one system or element shapes the input of/impacts another. For instance, increased private investments in clean energy in a city can feed back directly into the local economy through increased jobs, saved finances and improved working conditions. This further potentially feeds back into the local context that determines user groups and so on (also see examples in Mercure et al., 2016). Another example of feedback would be of the interaction of User groups and decentralised infrastructure leading to the creation of Prosumers significantly influencing the Provider landscape. However, the intensity of the feedback can vary between different subsystems. Feedback within a subsystem is likely to be the strongest, whereas it may reduce in its intensity for other external subsystems.

III) Material/ infrastructure – As mentioned earlier, it is the interactions of the technological or infrastructural layer with each agent that define the system structure in a socio-technical system like that of energy. Therefore, this component comprises all the technological, infrastructural, hardware artefacts, material networks from points of generation to delivery, and media used for acquiring, generation (in case of DESs), use and delivery of energy services at the urban level. The incorporation of information and communication devices like smart meters also add further nodes of potential intervention in the system attached to the myriad individual agents identified in the earlier section (I) (María, Durana, Barambones, Kremers, & Varga, 2014). This exacerbates the complexity as well as uncertainty in the system. While infrastructure required for transport is quite different from that of other energies, a complete representation of UESs will be incomplete without the consideration of transportation system - more so because of the rising trend of electrification of transportation. The technological/infrastructural layer undoubtedly is deeply interdependent on the infrastructure at higher administrative levels. This is more relevant for the local electricity grid or fuel supply which is connected to national grids or supply chains. On the other hand, it is also clearly dependent on the local energy resource and distribution infrastructure to enable decentralised energy production, delivery and exchange.

IV) Dynamics – Dynamics have been used quite loosely to depict multiple phenomena within complex systems. However, Batty (2009) articulates urban dynamics at the intra-urban level as 'different speeds of change' in different elements, sub-systems at different scales within the city (Batty, 2009). Arguing on these lines, Bale, McCullen, Foxon, Rucklidge, and Gale (2013), explicitly highlight temporal influences on energy systems in saying that changes that take place structurally over time as changes in population, lifestyles, technologies and costs exemplify energy system dynamics (Bale et al., 2013). Batty (2009) further differentiates between fast (daily changes) and slow dynamics. Dynamics of, or the degree of flux in any level of the unit is likely to impact the system properties like adaptability, co-evolution and self-organisation. Cities get their dynamic nature from a combination of agents and associated interactions and feedback which expectedly are likely to stem from

[7] http://www.iipnetwork.org/Industrial%20Restructuring%20in%20the%20Ruhr%20Valley.pdf; http://www.i-r.de/

[8] See discussion on energy distribution networks by Fichera et al., 2018

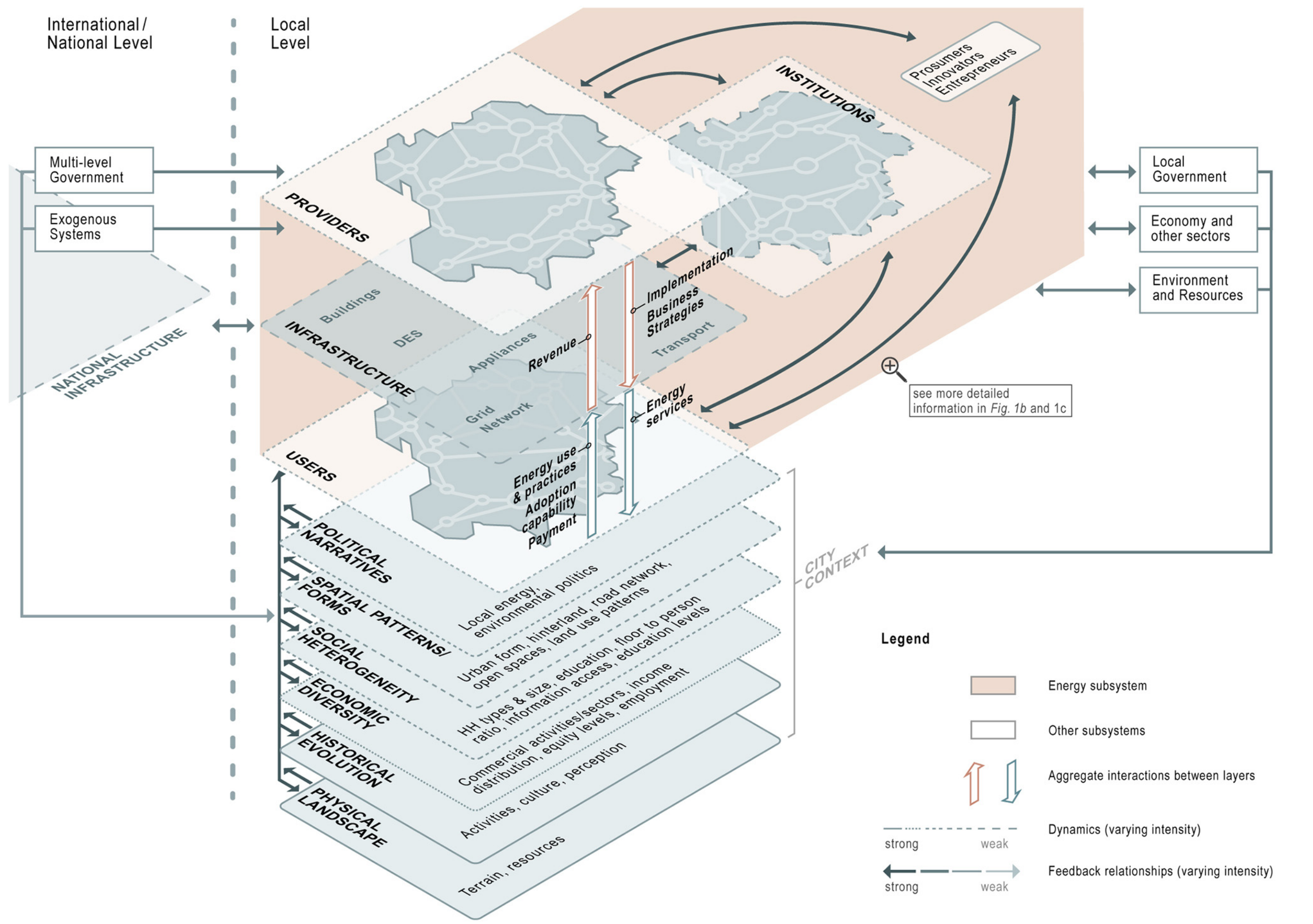

Fig. 1a. Urban energy complex system framework (complete).

the dynamic nature of the individual elements in a system (Barros & Sobreira, 2002). Literature specifically points towards the significance of the dynamic nature of contextual factors that can limit or facilitate agent interactions in complex systems or STS arenas (Edsand, 2016; May et al., 2016). From the policy makers point of view, the concept of dynamism can be useful to understand how entrenched a system, an interaction or an element is, to design interventions in an urban environment. Thus, it can serve to be particularly useful for the scholars studying obduracy and path dependencies in an urban system.

4.4.3 Proposed urban energy complex systems framework

Based on the above discussion, a visual framework of an urban energy complex system has been developed (Figs. 1a, 1b and 1c). The first figure (Fig. 1a) is the comprehensive framework representing UES as a complex system, while the subsequent two figures (Figs. 1b and 1c) zoom in on different aspects of the framework for a detailed understanding.

The complete framework is broadly divided into two levels combining the *national* and *international* (each element in the figures below have been italicised for easy reference) levels in the first and in the second, sets a detailed view on the *local level* or the city scale. At the higher levels, major external factors that are likely to affect the urban arena have been categorised under two broad headings of national *multi-level government* policy-making, decision and regulations as well as other *international exogenous factors* like the supply and international price of fuel and other economic factors. This level is also the host to any *national energy infrastructure* that extends to the urban level. The *local level* constitutes three broad elements of the 1) local context, 2) energy subsystem and 3) other urban subsystems. The framework then details out to focus on the subsystem of UES – a multi-layered system which has three agency layers of 1) *Users/consumers*;2) *Energy providers* 3) *Institutions*. Each of these agents are interconnected through *networks (intra-agent) and feedback (inter-agent)*. The *Infrastructure* layer is the intermediate level between *providers* and *users* comprising all the physical materials through which energy is delivered or serviced. Nodes on this layer like *appliances*, *distributed energy systems (DES)*, *buildings*, *transportation media* and such others are connected through the *grid networks* (e.g. *electrical grid,* roads or pipelines). The aggregated interactions between infrastructure and agents are represented by the broad hollow arrows. At this level of aggregation, the users, in exchange of the energy services provided by the infrastructural layer, *consume energy*, exhibit *adoption capability*, *make payments* whereas the *Providers implement* infrastructure or materials through carefully designed *business strategies* in return for *revenue*. The second important component of this framework is the *Context* that has been unpacked into six different layers (In accordance with the discussion on Context in section 4.4.1, the six layers have been identified as 1)Physical landscape; 2)Historical evolution; 3)Economic diversity; 4)Social heterogeneity; 5) Spatial patterns/forms; 6)Political narratives) each experiencing feedback relations amongst each other signifying the influence each layer is likely to have on other layers. Context impacts the users and the larger *urban energy subsystem* directly but also indirectly influences and is influenced by other subsystems (Fig. 1a).

The third component of the *local level* is the set of other urban subsystems that closely interact with the energy subsystem. Three broad levels of subsystems of 1) *Local Government*; 2) Sectoral

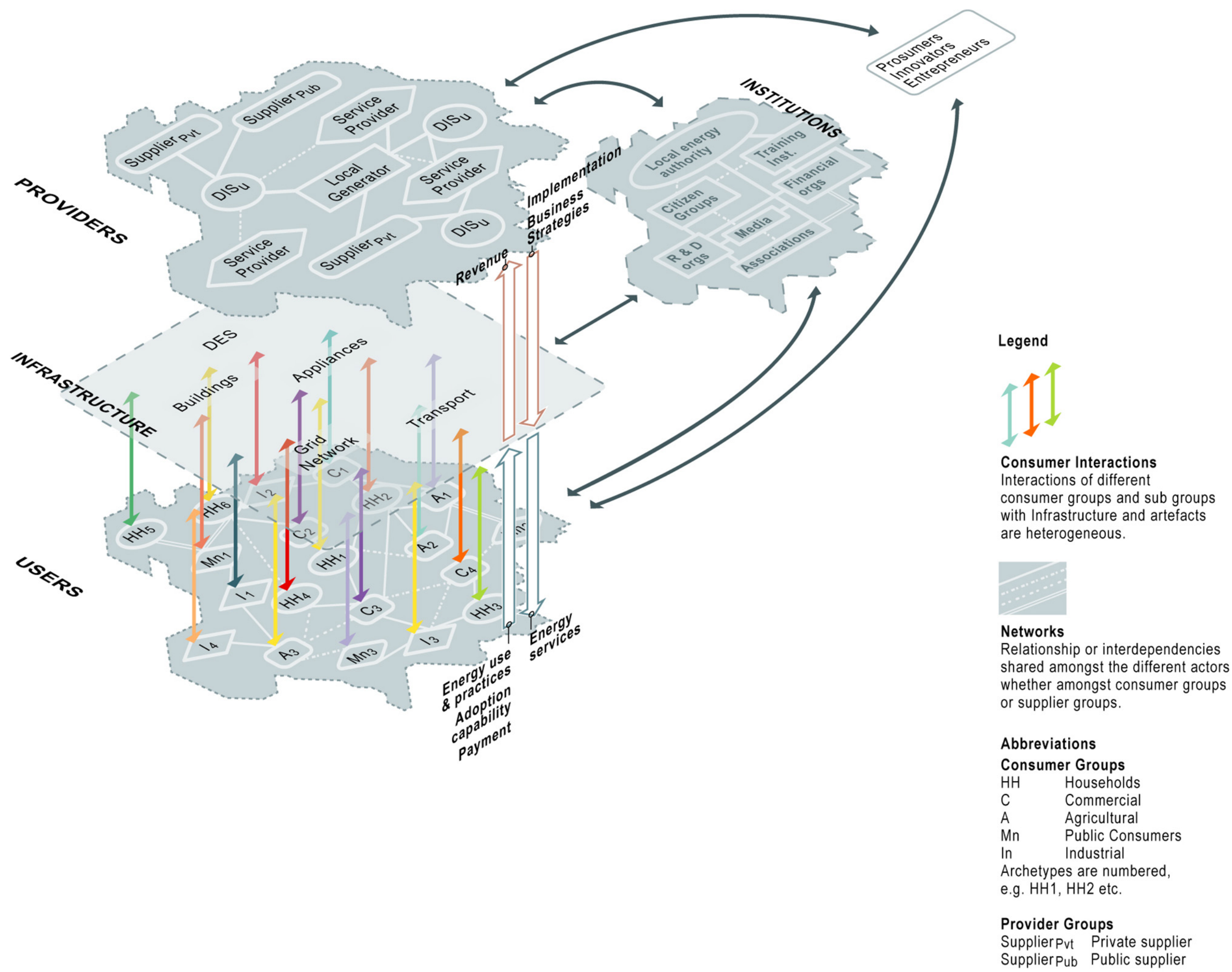

Fig. 1b. Urban energy complex system framework – Agents and Interactions.

subsystems like the *economy and other sectors* and lastly the 3) *Environmental and resource-based* subsystems that are affected by the subsystem but also impact the energy subsystem, have been identified within the framework.

The second figure zooms in on the energy subsystem illustrating the core elements like the three categories of agents and infrastructure layer and the interactions between them in detail. The agents have been divided into the broad categories of 1) *Users*: – who are categorised into broader user types based on functions and then further sub-divided into clusters/archetypes under each category; 2) *Providers:* though different for each city, for this framework - *Private Suppliers(Supplier pvt.), Service Providers, Local Generator, Distribution utilities(DIS_u)*; 3) *Institutions: Local Energy Authority, Citizen groups, Training institutes, R&D organisations, Media, Associations, Financial organisations*. All three agent groups are heterogeneous by nature and the different types of individual agents in each group have been demonstrated in the framework. As Users have been segregated further in energy studies, categorisation of the clusters within the broader User groups (*households, commercial, agricultural, industrial, municipal*) have been demonstrated through further sub groups like H_1, H_2 *or* A_1, A_2, and so on (Fig. 1b).

A critical aspect of the subsystem is the interaction between the different components. In this framework, the aggregate *agent-technology* (*User*) *interactions* have been further segregated wherein each agent or user cluster exhibits a unique interaction pattern with the infrastructural layer (shown through the difference in colour of arrows) and is simultaneously part of the social network with other user groups (shown as lateral diverse white connecting line between agents' groups). Similar networks also connect the Provider and Institution agent groups.

Another important interaction within the system is the *feedback* shared between these different components (solid blue lines) within the energy subsystem. As a result of this feedback phenomenon between the *Users* and the *Providers* layers, an additional level of complexity is brought in, giving rise to a new agent group of *prosumers*, *entrepreneurs* and *innovators* – *Users* who could also assume the role of *Providers* in the energy system.

The third figure highlights the *feedback relationships* (solid blue lines) between the components as well as the *dynamics* (brown contour lines) inherent in the different elements. *Feedback relationships* are, however, not uniform; the differing intensities try to capture the direct and indirect influences. For instance, feedback within the energy subsystem is likely to be stronger than outside it with the other subsystems. *Dynamics* of each element or subsystem, on the other hand, is represented through the contours of varying intensity based on the elements of the subsystems. For instance, the subsystem of *Energy Infrastructure* is expected to be obdurate due to their lock-in or path dependent nature and has been allotted a thicker line reflecting slower dynamics. However, the user subsystem is expected to be more agile anynamic and has been depicted accordingly with a dotted line (Fig. 1c).

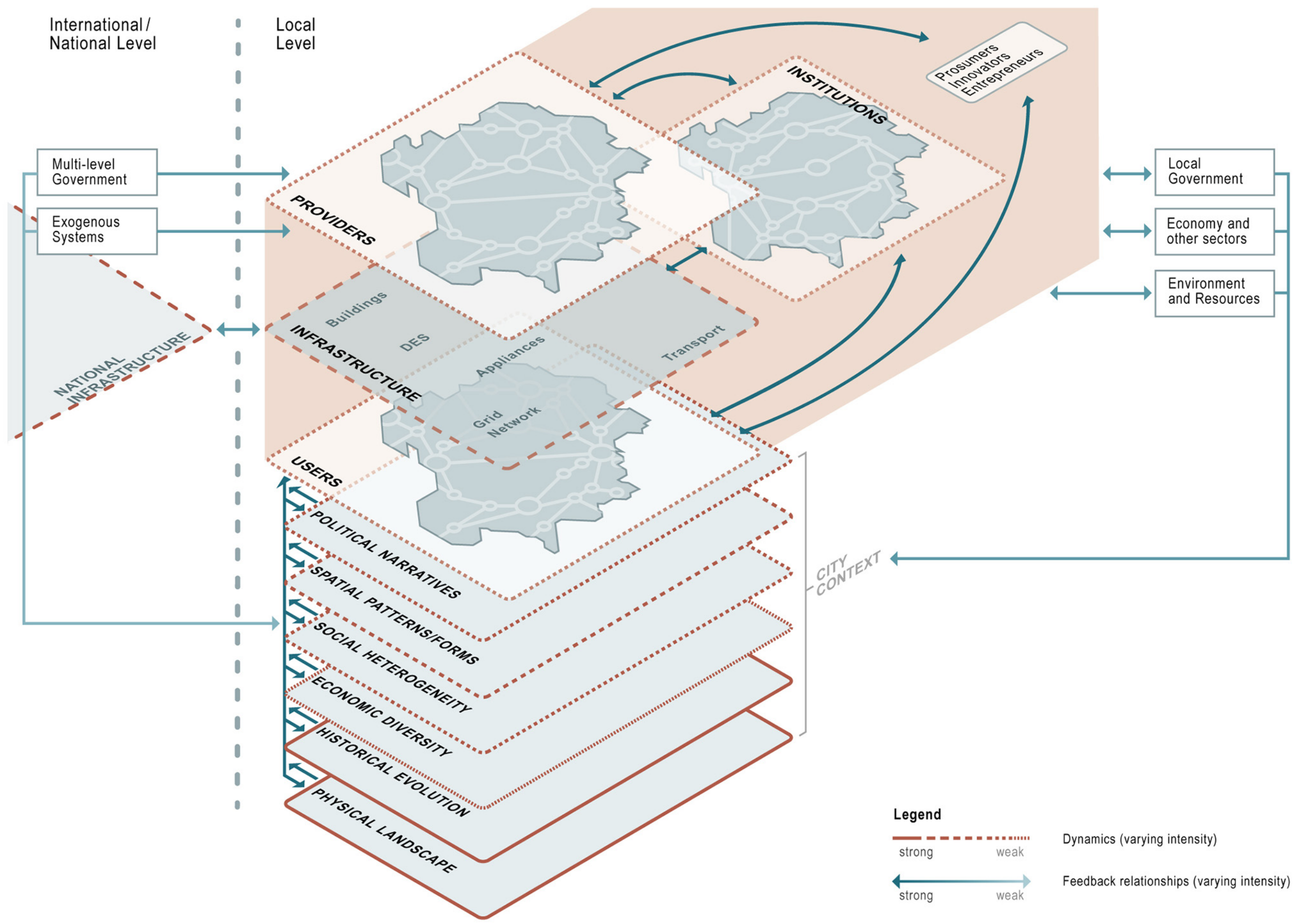

Fig. 1c. Urban energy complex system framework – Dynamics and Feedback.

4.5. *System properties of complex UESs*

System-wide properties distinguish complex systems from other simpler systems. These properties essentially reflect and explain the change that is often discontinuous and unpredictable. As Byrne and Bartiaux (2017) argue, that due to such properties, complex systems defy the reductionist notion that a system can be understood as the sum of components only and also that 'entities can be understood as themselves alone' (Byrne & Bartiaux, 2017). We highlight four such complex system properties most relevant and also documented in the context of UESs.

4.5.1. *Emergence*

Emergence is one of the most commonly agreed upon properties of a complex system and has its source primarily in the interactions of multiple complex entities within a system (Bale et al., 2015; Masys, 2006; Webb et al., 2017). Very simply put, emergence is the non-additive (Ryan, 2007) result of the myriad interactions between different subsystems and their components and networks. This phenomenon lends itself to the proverbial saying that the "whole is greater than the sum of its parts". Peter and Swilling (2014), have defined emergence as the product of uncertainty and non-linearity of agent behaviour – mechanisms that are at the core of complex systems due to the autonomous and non-rational behaviour of agents (Peter & Swilling, 2014). Emergence in a UES will result in aggregated trends and patterns and characterises the system and its subcomponents but cannot necessarily be predicted or simulated. Rebound effect in case of energy efficient interventions has been considered to be the classic case of emergence in energy systems (Jenkins, Middlemiss, & Pharoah, 2011).

4.5.2. *Self-organisation*

Self-organisation of a system is made possible primarily due to the agency of social agents in response to changes, opportunities, pressures and environmental dynamics in a complex socio-technical system. Therefore, it occurs at the agents' level but its manifestation has implications for the complete structure or existing regime (Peter & Swilling, 2014). The UES can be self-organising since there is no overall 'system architect', that is, there is no one actor responsible for all aspects of planning the entire system but can only be shaped by multiple policies and regulations from different agents. Formation of associations or citizen groups as representatives of a particular agent group can be considered as an attempt towards self-organisation in response to the lack of adequate political representation. Similarly creation of informal settlements and consequent instances of power theft or in areas of affordable transportation (Grubler et al., 2012) in developing country cities is a classic case of self-organisation phenomenon (Barros & Sobreira, 2002). From an urban energy governance point of view, self-organisation as a phenomenon has the potential to facilitate faster urban energy transition towards sustainability.

4.5.3. *Co-evolution*

Co-evolution refers to the transformation that individual components and their interactions undergo in relation to each other. It has been especially used to study the relationship between technologies and social practices (Rydin, Turcu, & Austin, 2011). A helpful framework in this area is by Foxon (2011) that highlights the co-evolutionary interactions between technologies, institutions, business strategies, user practices and eco-systems and has been applied to energy systems and infrastructure (Foxon, 2011). This can be an important aspect from the policy making perspective. The co-evolution of users to producers or prosumers of energy with the rise of Distributed Energy Systems (DES) within the urban arena is one such example (Adil & Ko, 2016).

4.5.4. Path dependency

In any complex system, with time, dynamic but dominant sets of artefacts, interactions and patterns develop and stabilize leading to path dependence. Agents or actors get accustomed to this set up and accept it as part of the system. This leads to the development of institutions, rules and norms. Path-dependence is a phenomenon particularly relevant for STS like energy (Bale et al., 2015; Unruh, 2000). Establishment of grids and historical prevalence of a centralised electricity supply system and social practices surrounding them has been a key barrier for decentralised RE systems to overcome. Within the urban arena, urban infrastructure such as roads, building type (old building infrastructure issues in European cities for instance) and spatial patterns add another layer of infrastructural lock-in leading to path dependence tendencies – largely a reflection of historical/contextual factors (Grubler et al., 2012). The degree of path dependence together with the established infrastructure, institutions and their rules, agents' habits, expectations and behaviours and incumbency of providers and suppliers reflect the adaptive or transformative capacity of the UESs as well.

5. Discussion – Relevance to planning and governance of urban energy transitions

5.1. How can the framework be used?

Several academic discussions have concluded by highlighting the need for an integrated outlook for contemporary cities (Keirstead et al., 2012; McCormick, Anderberg, Coenen, & Neij, 2013; Ramamurthy & Devadas, 2013). Recent urban sustainability literature has also acknowledged cities as complex socio-ecological-technical systems. However, this has not resulted in a framework to establish the ontological understandings of UESs as complex systems comprehensively (not just individual agents or certain sections). In this paper, we propose one such introductory framework that contributes broadly in four ways:

1) Creating a 'system awareness' of UESs – The large heterogeneous set of elements and interactions that lend energy systems their complexity, can be challenging to conceive, understand and appreciate. (Wolfram 2016), argues, 'system awareness' involving 'system dynamics, path dependencies and obduracies that undermine urban sustainability' constitutes the 'transformative capacity' of urban stakeholders. This framework then provides a conceptual map of UESs to foster a shared understanding and visualisation of UESs across different concerned disciplines of transitions, urban energy modelling, urban policy-making and planning.
2) UESs as embedded, interlinked and integrated – The framework also establishes an alternate ontological foundation for cities wherein cities and their energy systems are looked at as highly dynamic, integrated systems that are only part of a larger whole (whether in terms of infrastructure, market, or regulations). This moves away from the conventional static view of urban areas that allows limited interactions with other sectors within the city.
3) Disaggregated, modular view – The 'systems of systems of systems' view that is complex systems - the foundation of this framework – allows a large variety of elements and agents to come together across the different scale. For instance, agents ranging from individuals to social or broader user groups can become the object of study or intervention depending on the scale or purpose of investigation and yet can be seen as part of the larger system. Each individual, group or community are then subsystems in their own right. This provides room for heterogeneity as a fundamental concept and consequently provides for flexibility in research and governance strategies.
4) Contextual conditioning – Lastly, the framework is also able to bring out the contextual grounding of urban areas and its implication on energy systems – how it shapes and is shaped by the energy system and others. This has been a matter of discussion across the disciplines of urban infrastructure with limited attempts towards its operationalisation.

In more quantitative and application-oriented disciplines, a common understanding of UES as this one can also boost concerted efforts in terms of data collection, planning, identifying opportunities and barriers between policy-makers, governing institutions, modellers and technical experts. While individual segments of this framework have been dealt with by several experts separately, through the use of a complex-systems approach, we have brought together a comprehensive view specifically for urban energy landscape. Having established this, it needs to be kept in mind that this framework is only a first step towards establishing such a framework. Further work could involve not only identifying further details but also establishing more concretely the abstract and qualitative concepts like context, interactions, feedback loops through empirical means. Though the article attempts to speak to a large set of disciplines especially in the social sciences study of urban energy, some of the specific communities where this framework can find value have been discussed below:

5.2. Policy-makers

The diverse nature of cities across the world and the lukewarm response of the existing sustainability strategies have invoked the need for a bottom-up paradigm in urban sustainability governance. At the outset then this framework based on complex systems understanding arms policy-makers with a stronger argument for decentralised governance for cities.

To understand the complexity of the whole system is an overwhelming task as it is frequently misunderstood that there is a need to understand every subsystem to the same degree of detail as the subsystem in which a person has her key field of expertise. In this respect, complexity can become frightening for practitioners since it is not possible to fully comprehend a complex system entirely. However, especially with the increasing focus on the imperative of sustainable development(s) a change from single-dimensioned outcomes towards a process oriented 'reflexive governance' is indispensable. A linear approach to policy making that treats problems as predominantly separate, isolated phenomena is inclined to create externalities and unintended effects (Jan-Peter, Dierk, & René, 2006).

It would be highly interesting to scientifically analyse which concepts policy makers have of UESs. How they would describe the system, including the questions which subsystems they would see or not see as being relevant for their decision making. Our hypothesis at this stage is that many experts have biased views based on their specific field of expertise, educational disciplines etc. In other words, the sociology of different 'tribes' of policy makers determines their ontology. This would have a strong impact on how problems are being framed - or more basically if and how they are taken into account in the first place - which again largely predefines which kind of solutions are being explored. In contrast, we claim that using the results of complex system theory – a 'conceptual map'- can help to gain new perspectives on the UES and is more appropriate to developing bespoke and inclusive policy strategies, that tap into local opportunities and potential, are in line with the properties and dependencies of the system and avoid unintended consequences. The scale of urban areas could make this an acceptable proposition for policymakers. A notable example in this could be that of fuel poverty related issues in many developed world cities. It makes a significant difference whether fuel poverty is addressed exclusively as a techno-economic issue in households or whether it is predominantly seen as a health and housing issue for poor households that has clear sustainability dimensions (Bale et al., 2012).

Even if in principle the technologies employed may be similar, the process of designing the strategies to solve the problem, whom to involve, which funds/opportunities to tap for support etc. may be very different - leading to quite different solutions in the end. However, this ontological understanding of complex UESs necessitates that policy makers work together with the modelling and governance communities and hence a crucial need for a common understanding of the system as a whole arises.

One of the frequently agreed complex systems characteristics particularly relevant for policy makers is the invariable uncertainty and unpredictability of the systems originating from the nonlinear interactions of the components (Biggs et al., 2015; Crawford, 2016; Loorbach, 2010). Therefore, both policy-making and assessment could benefit greatly by internalising these possible eventualities of any policy decision. A shift towards incremental and recursive policy making from a deterministic approach has been considered a possible solution to address this.

5.3. Sustainability transitions

The scholarship of sustainability transitions has concentrated on the process of conceptualising, implementing and managing change in social systems vis-à-vis technological or ecological processes. The framework introduced in this paper contributes to conceptualising the underlying 'system' within which the change is to be implemented or managed through a complexity lens.

At the core, one of the most commonly deliberated frameworks, multi-level perspective (MLP) analyses the interaction between agency and structure across different levels - niches, regimes and landscapes (Wittmayer, Avelino, van Steenbergen, & Loorbach, 2016). The framework presented makes it possible to situate these interactions within the complexity of UESs. Therefore, transition scholars can use this framework, for instance, to identify niches (that could vary from being individuals to communities or firms), their context and interconnections that give them the fuel to challenge the regime. A complex system view then frames urban energy areas or the 'regime' of transition as a highly dynamic and connected *regime* that is also constantly transitioning. As Holtz et al. (2008) raise, "What is seen as a regime will strongly influence the framing of research questions as well as the selection of actors in participatory processes, like transition management; and it will shape the scope of solutions actors may suggest" (Holtz et al., 2008). The task for sustainability transition management scholars is then to channel/direct the transition of this complex regime towards the direction of sustainability objectives systemically.

5.4. Urban energy system modellers

A complex systems approach has been considered appropriate for modelling urban energy systems (Bale et al., 2015; Keirstead et al., 2012; Mercure et al., 2016). As the modelling community increasingly answers the call for an integrated approach towards simulating UESs, having a common or 'shared' ontology, becomes important for developing a common language between policy makers and modellers. A commonly agreed framework, as the one suggested here, can be key to articulating the data points and collection requirements for adequate simulation. Similarly, the modularity possibilities of the framework can facilitate a joint exercise of understanding and modelling specific localised subsystems while keeping in mind the larger integrated whole.

More importantly, as understanding of the complex system properties and its implications weigh in on the notion of uncertainty and unpredictability the results from modelling exercises will need to be assessed as more indicative rather than an absolute. Each result will need to be seen considering the myriad interactions of one system with others. In essence, contingency planning or making room for diversions in case of planning interventions based on modelling results will be a requirement in future simulation and subsequent policy making of UESs.

However, a more ambitious utilisation of the framework would be to simulate the multitudinous but often indeterminate interactions manifesting in agent-technology relationships, socio-economic and technical networks, and feedbacks and to that extent qualify causal and non-causal relationships. The desirable outcome would be an integration of multiple decentralised qualitative and quantitative models that produce system wide probabilistic intended or unintended effects of policy interventions; recommend least cost or least regret techno-economic policies interventions; or suggest multiple actor-based intervention strategies.

6. Conclusion

The paper uses diverse academic developments relevant to urban energy studies and findings across multiple fields of complex systems to offer a preliminary framework for a 'shared understanding' of the complex UES. It identifies and unpacks each element and interaction and links to wider elements beyond the immediate subsystem of urban energy systems.

We see a great potential in the framework for policy makers as well as practitioners in government and administration to get a better sense of the different components, interactions, dynamics and potential impacts of policy interventions in UESs and thus to make informed policy decisions. Therefore, through this framework, we hope to encourage appreciation of the diverse and heterogeneous nature of these systems and the dependence of the system as a whole on the continuously evolving interactions within and outside of this diversity. Essentially the framework contributes to a much-needed departure from the traditional reductionist approach involving just the binaries of technologies and users. This common imagery amongst multiple disciplines and stakeholders is expected to have far reaching impacts on designing interventions for enabling the transition of UESs towards sustainability – especially on the front of technology adoption, behavioural change, urban planning, energy efficiency amongst others. It is also expected that this work ushers further research on 1) empirical application of the framework across multiple cities to further qualify and enrich it; 2) identification of data points and creation of a data map; 3) establishing linkages and applicability in other disciplines concerning urban energy; 4) testing the framework approach through participatory modelling methods (Voinov & Bousquet, 2010).

Up to this point, the concept has been described and the framework fleshed out for further scientific debate. One challenge will be to develop it further, grounding it empirically, including means of communicating the concept as well as the results stemming from its application, in such a way that it is digestible for policy makers. In this respect we would not aim at policy makers having to understand the concept in detail, but rather at developing tools and processes in the science/policy making interface which are based on the framework. For instance, developing city-wide models or maps based on such a framework could be an invaluable resource for urban policy makers. The applicability for the policy making process should of course not end at the conclusion that it is important for decision makers to be aware of the characteristics of complex systems. But as all changes start with the recognition and appreciation of phenomena, this framework could serve as a crucial starting point. The current framework is in no way considered to be set in stone. In the long run, a complex-systems approach to UESs and its academic and empirical application is expected to further add to this framework. This paper provides only a preliminary, yet significant, contribution towards this goal.

Declarations of interest

None.

Funding

This work was supported by the following organisations; Engineering and Physical Sciences Research Council, UK under a fellowship for CSEB [grant number EP/K022288/1], and International Climate Protection Fellowship (2016-17) by Alexander von Humboldt Foundation, Germany -, and the Wuppertal Institute for Climate, Environment and Energy, Germany. We are thankful for the support and for making this research possible.

Acknowledgements

We would like to the two anonymous referees for their feedback on earlier versions of this paper. We would also thank the illustrator of the Framework in the article.

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